Differential Lung Toxicity of Biomass Smoke from Smoldering and Flaming Phases Following Acute Inhalation Exposure

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Abstract & Background

We previously demonstrated that, on a mass basis, lung toxicity associated with particulate matter (PM) from flaming smoke aspirated into mouse lungs is greater than smoldering PM. This finding however has to be validated in inhalation studies to better predict real-world exposures. Thus, we modified an existing combustion system to precisely control and maintain smoke concentrations during the combustion process. We generated biomass smoke from peat and eucalyptus fuels under smoldering and flaming phases for up to 1 hour, and measured PM and volatile organic compounds (VOCs) levels. Smoldering PM levels were ~10 times higher than flaming PM with carbon monoxide (CO) held at similar levels to equalize potentially interfering CO health effects. Mice were exposed by inhalation for 1 hour/day for 2 days and then assessed for lung toxicity at 4 and 24 h after the second exposure. PM levels were ~40 and ~4 mg/m3 under smoldering and flaming phases, respectively, while CO levels ranged from ~80 to 110 ppm for all exposures. Notably, VOCs/PM ratios were higher (up to 7 times) in flaming than smoldering smoke. Smoldering peat and eucalyptus smoke elicited significant inflammation (neutrophils) in mouse lungs at 4 h post-exposure while flaming smoke from either fuel caused even greater lung inflammation at 24 h post-exposure. Similarly, a significant increase in an index of airflow obstruction was observed in mice exposed to flaming peat and eucalyptus, and smoldering eucalyptus smoke immediately after each day of exposure. These results suggest that although flaming smoke contains much less PM mass than smoldering smoke, the health risk of this exposure is, on a mass basis, greater than that from smoldering emissions. These observations support the concept that health risks of smoke exposure vary depending on the type of fuel and combustion conditions. [This abstract does not represent EPA policy]

Health impacts of wildland fire smoke

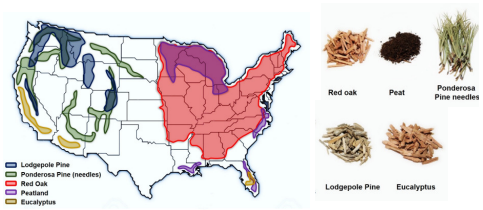
- Wildland fire smoke is a hazardous mixture of gaseous emissions and particulate matter (PM).
- It is not well understood if the health impacts of wildland fire smoke are influenced by fuel types or combustion conditions.

Research hypothesis

- Toxicity of smoke emissions from wildfires varies depending on the type of fuel, combustion conditions, and particle chemistry.

Materials & Methods

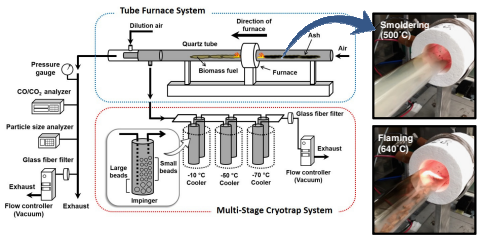
Tested biomass fuels and their distribution in the United States



- Red oak (obtained from the Air Pollution Prevention and Control Division at the US EPA)
- Peat (collected from the coastal plain of the eastern North Carolina, ARNWR)
- Ponderosa pine needles (provided by the Missoula Fire Sciences Laboratory)
- Lodgepole pine (provided by the Missoula Fire Sciences Laboratory)
- Eucalyptus (purchased from a local supplier)

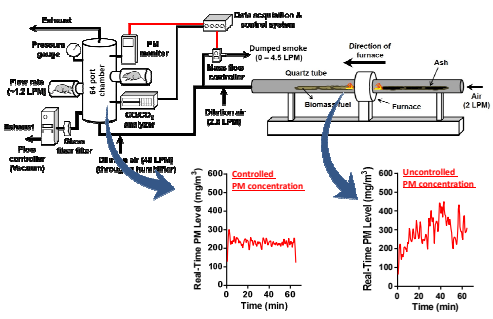
Aspiration Exposure Study

Biomass combustion and smoke collection system



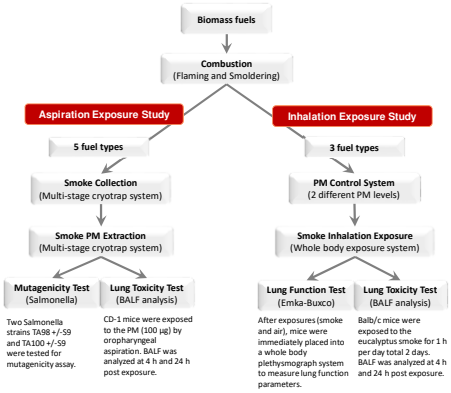
Inhalation Exposure Study

Automated combustion and smoke inhalation system



Materials & Methods

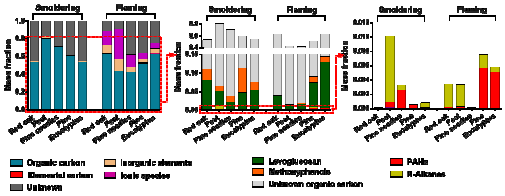
Flow diagram of the biomass smoke study



Results

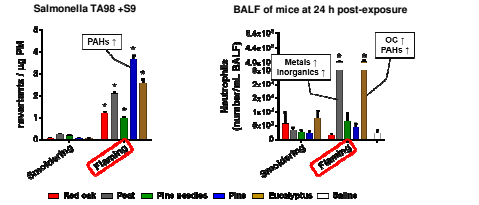
Aspiration Exposure Study

Figure 1: Chemical mass fractions of the biomass smoke PM (an equal mass basis)



- Levels of organic carbon and levoglucosan were dependent on fuel types (woody vs. non-woody fuel).
- Levels of ions, inorganic elements, and methoxyphenols were dependent on combustion phases (smoldering vs. flaming).

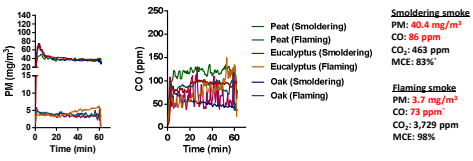
Figure 2: Mutagenic and lung toxicity potencies of the PM (toxicity/mass of PM)



- Mutagenicity and lung toxicity of the PM were greater in the flaming phase smoke than the smoldering smoke on an equal PM mass basis.

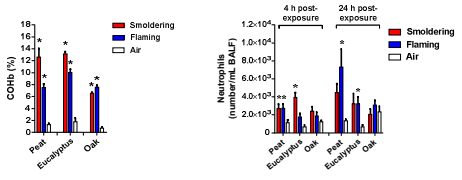
Inhalation Exposure Study

Figure 3: Biomass smoke properties in the inhalation chamber



- Smoldering PM levels were ~10 times higher than flaming PM with CO held at similar levels to equalize potentially interfering CO health effects.

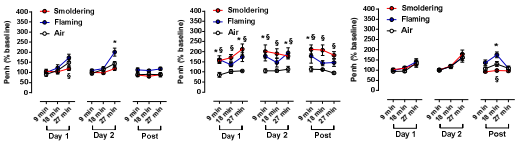
Figure 4: Biological responses to the biomass smoke exposure



- Peat smoke produced under either combustion conditions caused similar increases in neutrophil (PMN) influx at both timepoints despite the flaming PM concentration being 10-fold lower.
- PMN responses to eucalyptus smoldering were higher at 4 h than flaming although effects were equivalent for both conditions by 24 h.
- No PMN effect was seen following exposure to either combustion condition of oak.

Results

Figure 5: Penh responses to the biomass smoke exposure



- Penh values were measured at 9 min intervals in the 30 min before exposure (baseline), right after exposures (Day1 and Day2), and 24 h after exposure (Post), respectively.
- A significant increase in airflow obstruction (as measured by Penh) was observed in mice exposed to flaming (*) peat and for both flaming (*) and smoldering (§) eucalyptus immediately after each day of exposure, in agreement with the inflammation results.

Figure 6: Lung toxicity: Aspiration vs. Inhalation

Aspiration PM dose

Smoldering condition: 100 µg PM → ~80 µg PM*
Flaming condition: 100 µg PM → ~80 µg PM*

*It was assumed that ~80% of aspirated PM (100 µg PM) are deposited in mouse lungs (**Foster et al., J Appl Physiol, 90:111, 2001**).

Inhalation PM dose

Smoldering condition: ~40 mg/m³ → ~40 µg PM*
Flaming condition: ~4 mg/m³ → ~4 µg PM*

*It was assumed that ~30% of inhaled PM (~130 and ~13 µg PM for smoldering and flaming exposure, respectively) are deposited in mouse lungs (**Foster et al., J Appl Physiol, 90:111, 2001**).

Lung deposited PM doses from each delivery method

			Peat	Eucalyptus	Oak
Aspiration	4 h	Smoldering	80	80	80
		Flaming	80	80	80
	24 h	Smoldering	80	80	80
		Flaming	80	80	80
Inhalation	4 h	Smoldering	40	40	40
		Flaming	4	4	4
	24 h	Smoldering	40	40	40
		Flaming	4	4	4

PM dose ratio of aspiration to inhalation

			Peat	Eucalyptus	Oak
Aspiration /Inhalation	4 h	Smoldering	2	2	2
		Flaming	20	20	20
	24 h	Smoldering	2	2	2
		Flaming	20	20	20

Neutrophil numbers from each delivery method

			Peat	Eucalyptus	Oak
Aspiration	4 h	Smoldering	3195	8544	2180
		Flaming	23834	16941	7096
	24 h	Smoldering	3320	7617	5678
		Flaming	68522	63368	1388
Inhalation	4 h	Smoldering	2709	3949	2398
		Flaming	2744	1761	1884
	24 h	Smoldering	4481	3242	2041
		Flaming	7305	3230	3094

Neutrophil number ratio of aspiration to inhalation

			Peat	Eucalyptus	Oak
Aspiration /Inhalation	4 h	Smoldering	1	2	1
		Flaming	9	10	4
	24 h	Smoldering	1	2	3
		Flaming	9	20	0

- PM dosimetry analysis results show good concordance in responses between aspiration and inhalation studies depending on type of fuel and combustion conditions.

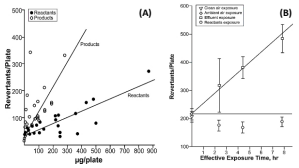
Conclusions

- Type of fuel and combustion conditions have dramatic differences in emission characteristics, mutagenicity, and lung toxicity.
- Forest composed largely of eucalyptus and pine produced emissions that could cause greater health effects than comparable fires from forests composed of the other types of biomass fuels.
- Inhalation studies conducted with the automated combustion system can validate responses seen in aspiration exposure studies after adjustment for PM dosimetry.
- The automated combustion system is capable of controlling combustion phases and PM concentrations and also can be employed for health risk assessment from inhalation exposure to wildfire smoke.

Future Work

Photochemically aged biomass smoke study

Mutagenicity of fresh and aged wood smoke (Kleindienst et al. ES&T, 20:493, 1986)



(A) Dichloromethane extracts of PM were 3X more mutagenic in TA98 (+/- S9) with UV lights on (reactants) than when lights were off (products).

(B) Gas-phase emissions from combustion of burning oak produced 36 revertants/h in TA100 (same + or – S9) with UV lights on. No mutagenicity was observed with lights off.

Diagram of an aged biomass smoke inhalation system